Production of nuclei and hypernuclei in relativistic ion reactions

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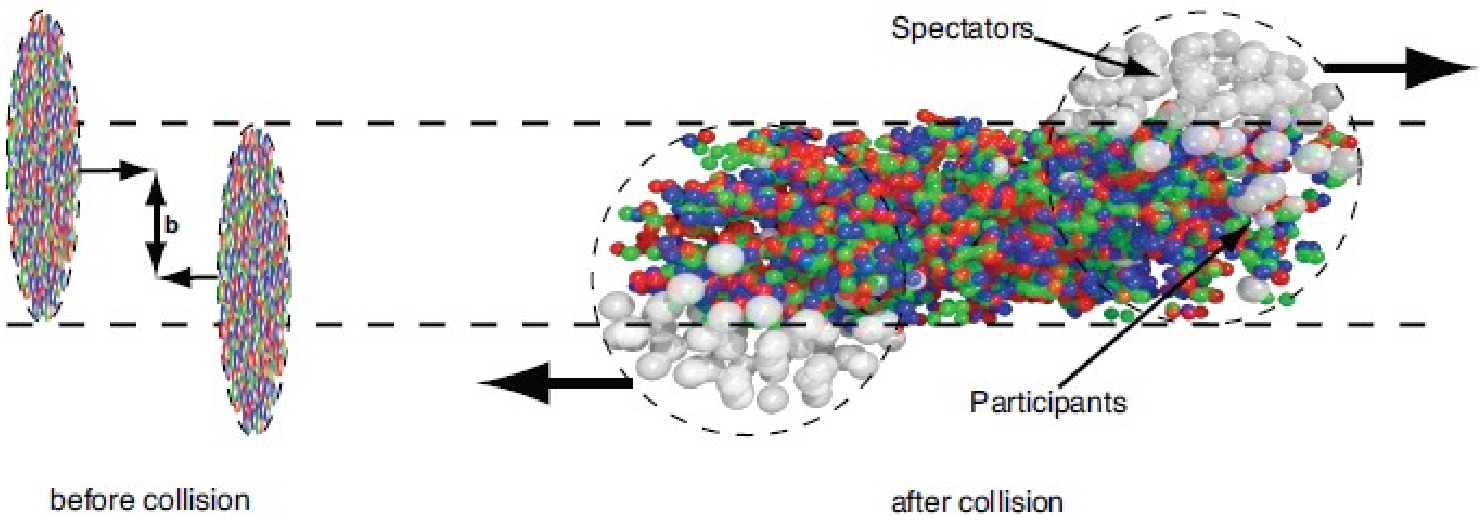
QM2022 conference (Krakow, Poland)

April 4-10, 2022

Qualitative picture of dynamical stage of the reaction leading to fragment production (e.g., UrQMD calculations)



Fragment formation is possible from both participants and spectator residues

UrQMD PHSD DCM GiBUU

Production mechanisms of nuclear cluster species including anti-matter, hyper-matter in relativistic HI and hadron collisions:

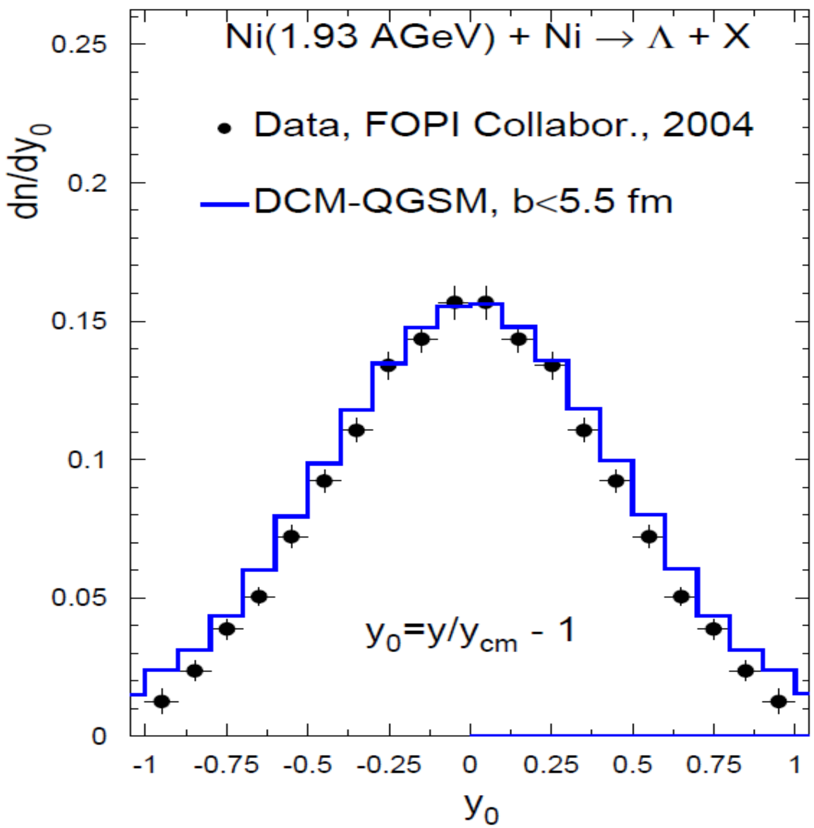
- Production of all kind of particles (anti- , strange, charmed ones) in individual binary hadron collisions. Effects of nuclear medium can be included.
- Secondary interactions and rescattering of new-born particles are taken into account. (Looks as partial 'thermalization'.)
- Nucleation process of produced baryons into composite (normal. exotic, anti- , hyper-) nuclear species.
- Capture of produced baryons by big excited nuclear residues.

Statistical decay of excited nuclear species into final nuclei

- Multifragmentation into small nuclei (high excitations),
- Evaporation and fission of large nuclei (low excitations),
- (Fermi-) Break-up of small nuclei into lightest ones.

All transport modes predict similar picture: Hyperons can be produced at all rapidities, in participant and spectator kinematic regions.

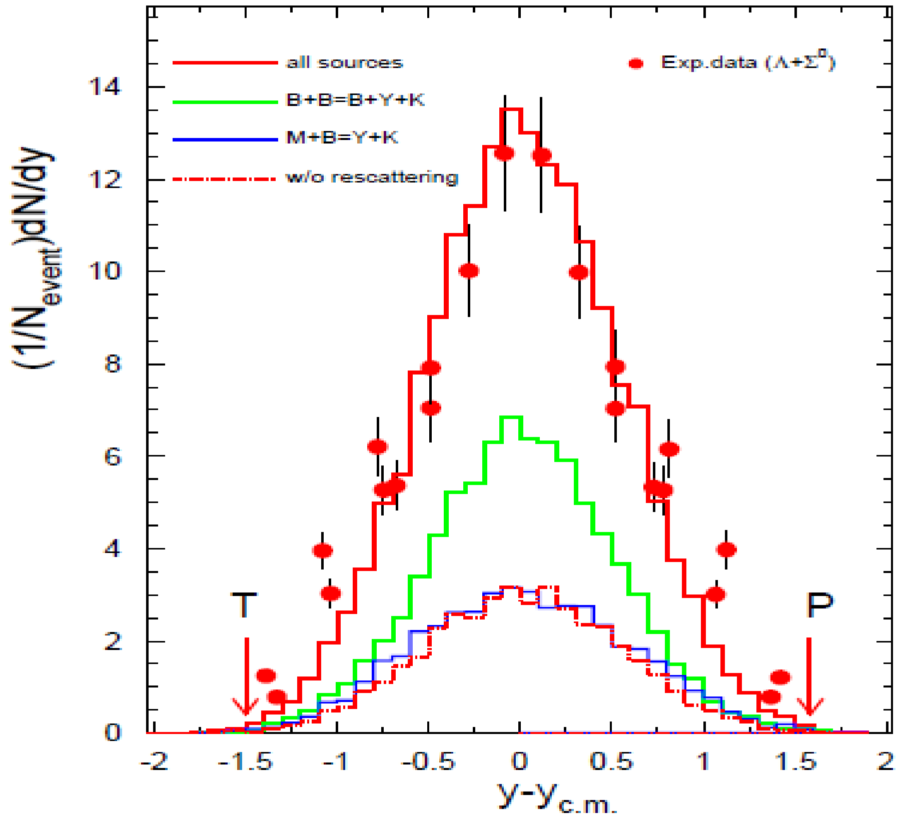
Wide rapidity distribution of produced Λ!



Calculation: DCM PRC**84**(2011)064904

S.Albergo et al., E896: PRL88(2002)062301

Au(11AGeV/c)+Au



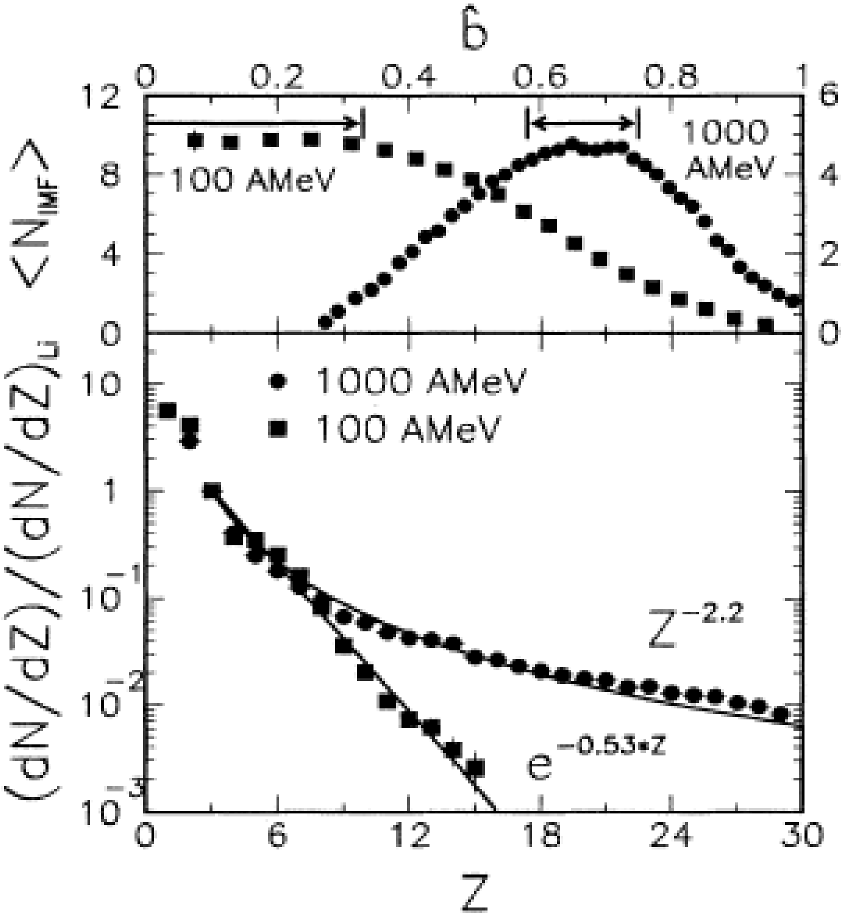
Long tradition of fragment measurements in high energy reactions:

Fragment production in Au+Au collisions: ALADIN (GSI) + Multics/Miniball (MSU) experiments

(G.J.Kunde et al., PRL 74, 38 (1995))

Difference of fragment yields obtained in spectator region (very broad distribution) and in central collisions (exponential fall of yields with mass/charge): Indication on different fragment production mechanisms.

Also there is a fragment flow in central collisions (high kinetic energies per nucleon respective to c,m, of decaying system).



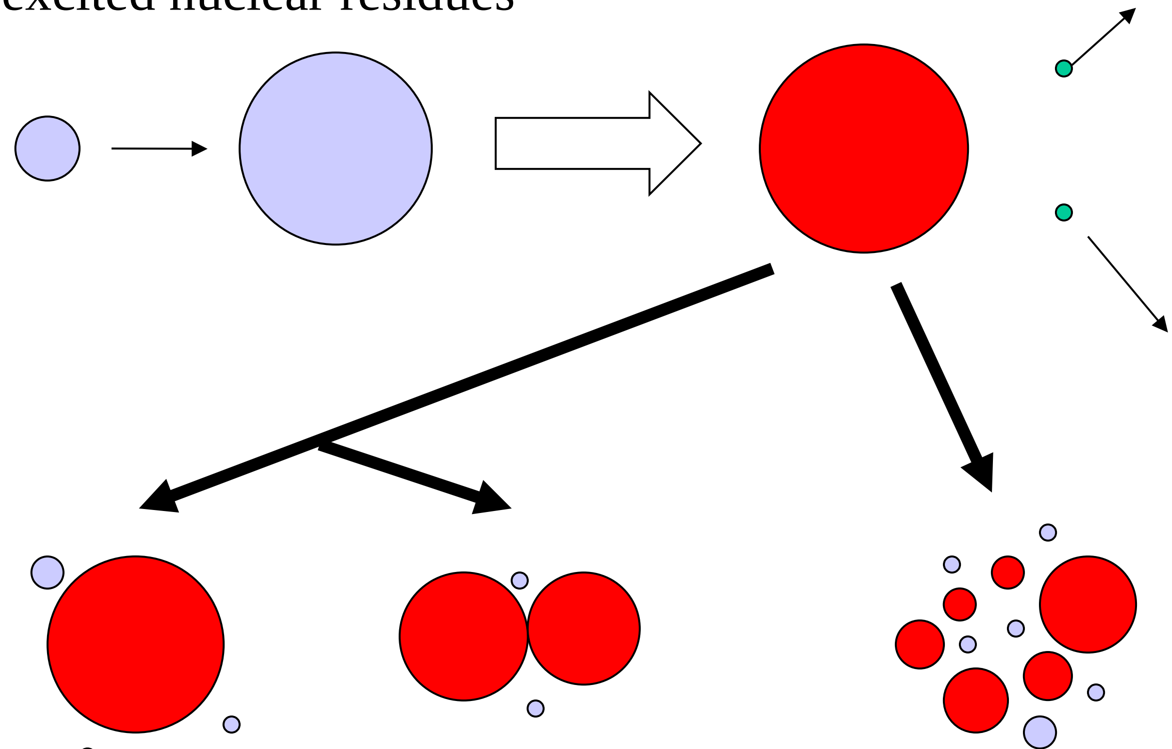
Low/intermediate energies: hadron/lepton collisions with nuclei, the same mechanisms in peripheral ion collisions

Dinamical stage with particle emission and production of excited nuclear residues

Preequlibrium emission + equilibration

Statistical approach

N.Bohr (1936)



Compound-nucleus decay channels (sequential evaporation or fission) dominate at low excitation energy of thermal sources E^{*}<2-3 MeV/nucl

N.Bohr, J.Wheeler (1939)
V.Weisskopf (1937)

starting 1980-th :

At high excitation energy E^{*}>3-4 MeV/nucl there is a simultaneous break-up into many fragments (e.g. SMM: Phys.Rep.**257**(1995)133)

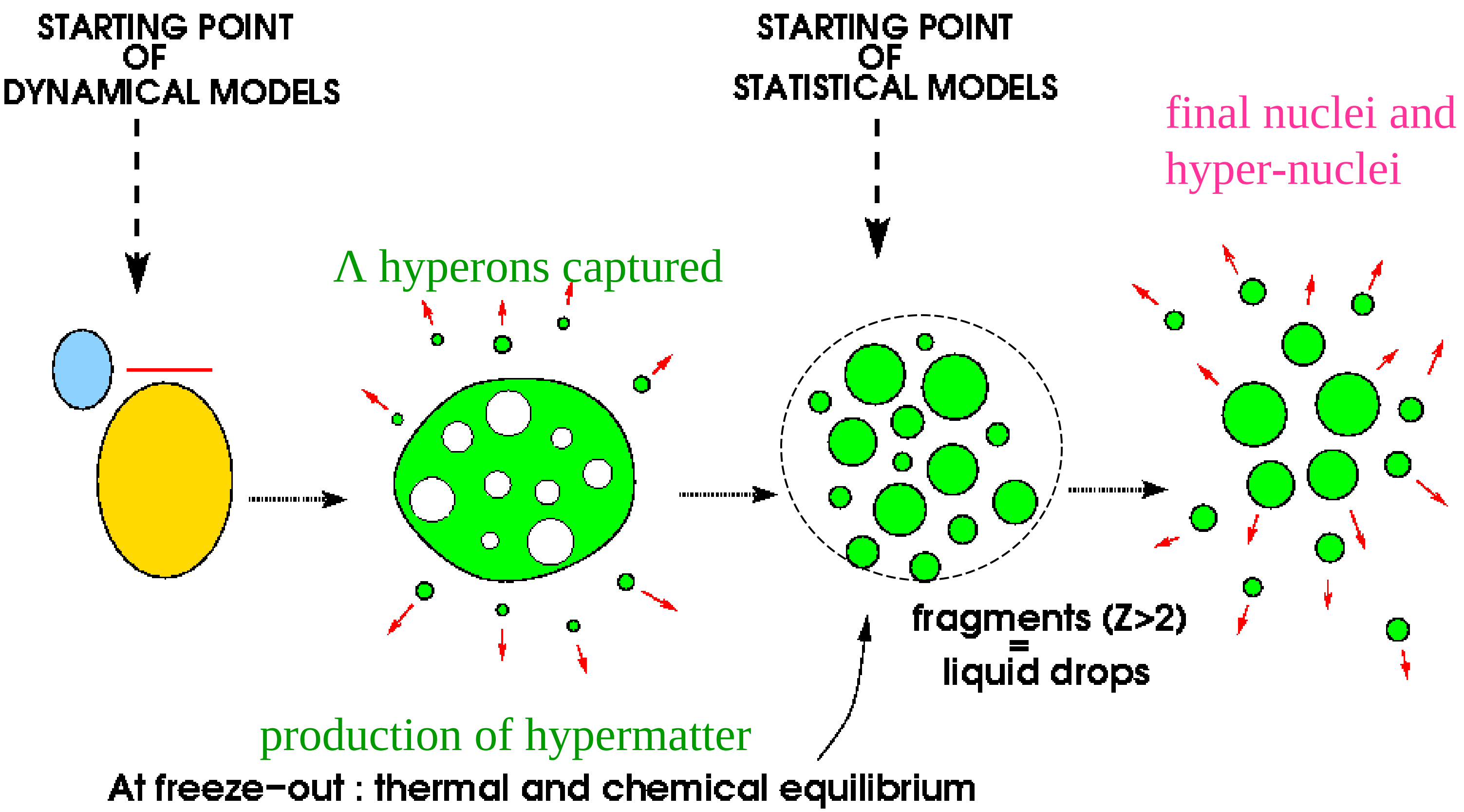
evaporation fission multifragmentation

A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

Generalization: statistical de-excitation model for nuclei with Lambda hyperons

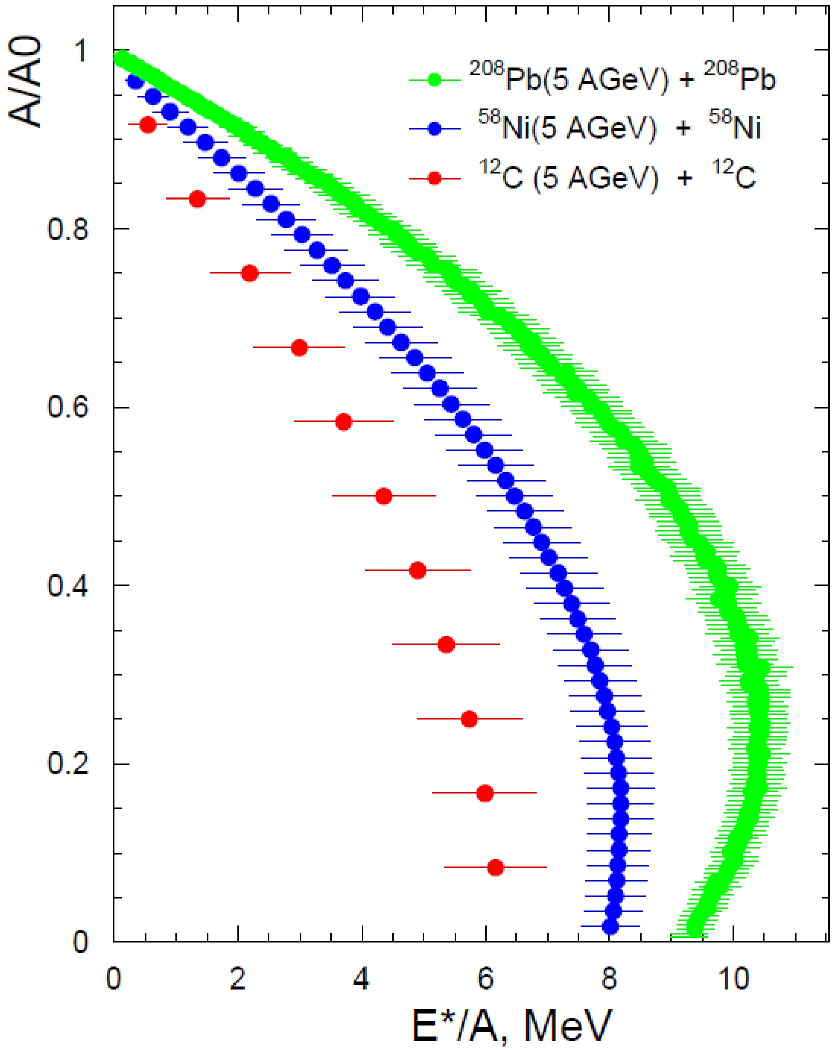
In these reactions we expect analogy with

multifragmentation in intermediate and high energy nuclear reactions
+ nuclear matter with strangeness



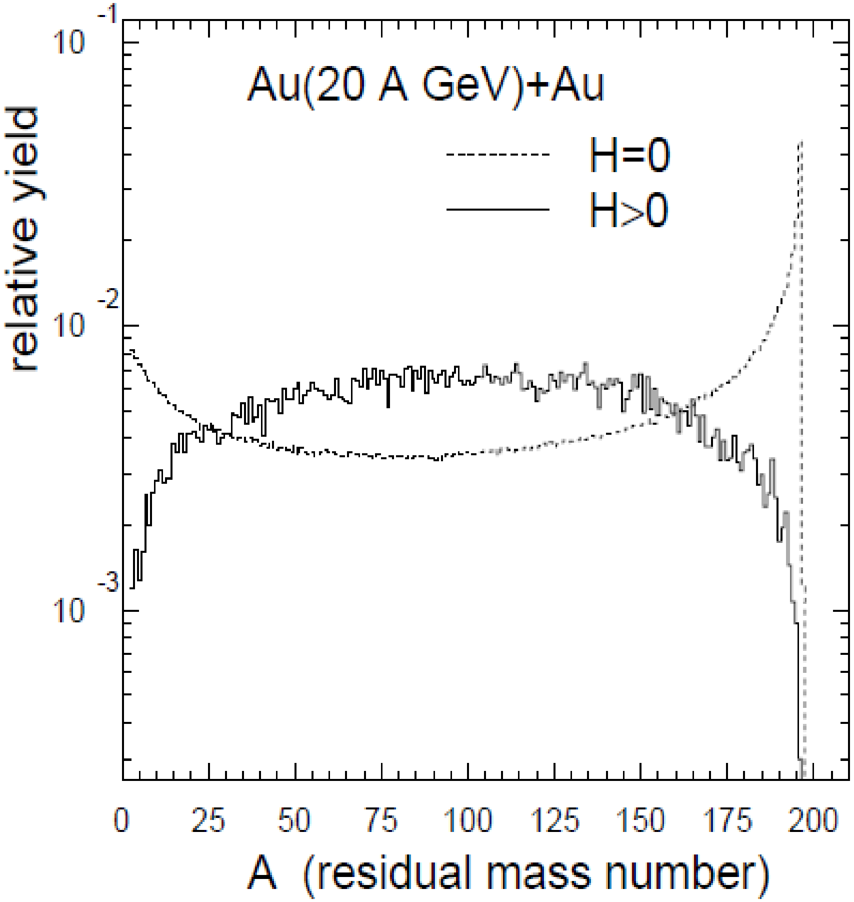
Excitation energies of the nuclear spectator residuals

DCM : PRC95, 014902 (2017)



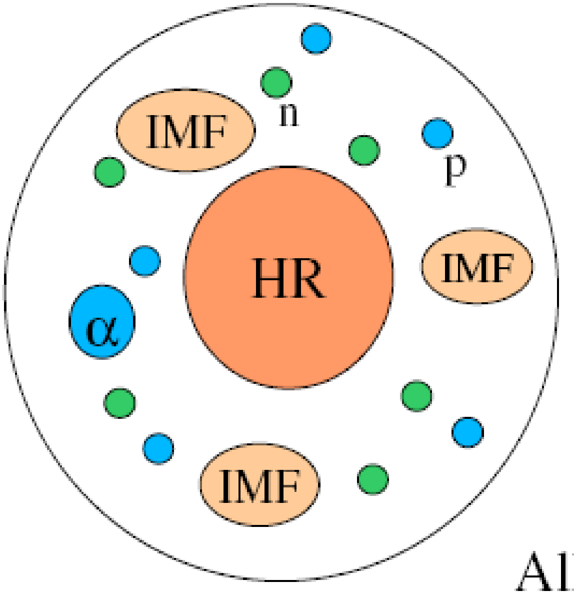
PRC84, 064904 (2011)

Masses of projectile residuals produced at dynamical stage (6b: H=0, 0.2b: H>0)



Statistical Multifragmentation Model (SMM)

J.P.Bondorf, A.S.Botvina, A.S.Iljinov, I.N.Mishustin, K.Sneppen, Phys. Rep. **257** (1995) 133



Ensemble of nucleons and fragments in thermal equilibrium characterized by

neutron number N_0
proton number Z_0, $N_0+Z_0=A_0$
excitation energy $E^*=E_0-E_{CN}$
break-up volume $V=(1+\kappa)V_0$ freeze-out

All break-up channels are enumerated by the sets of fragment multiplicities or partitions, $f=\{N_{AZ}\}$

Statistical distribution of probabilities: $W_f \sim \exp\{S_f(A_0, Z_0, E^*, V)\}$

under conditions of baryon number (A), electric charge (Z) and energy (E*) conservation, including compound nucleus.

PHYSICAL REVIEW C, VOLUME 62, 024616

Two-stage multifragmentation of 1A GeV Kr, La, and Au

EOS collaboration: fragmentation of relativistic projectiles

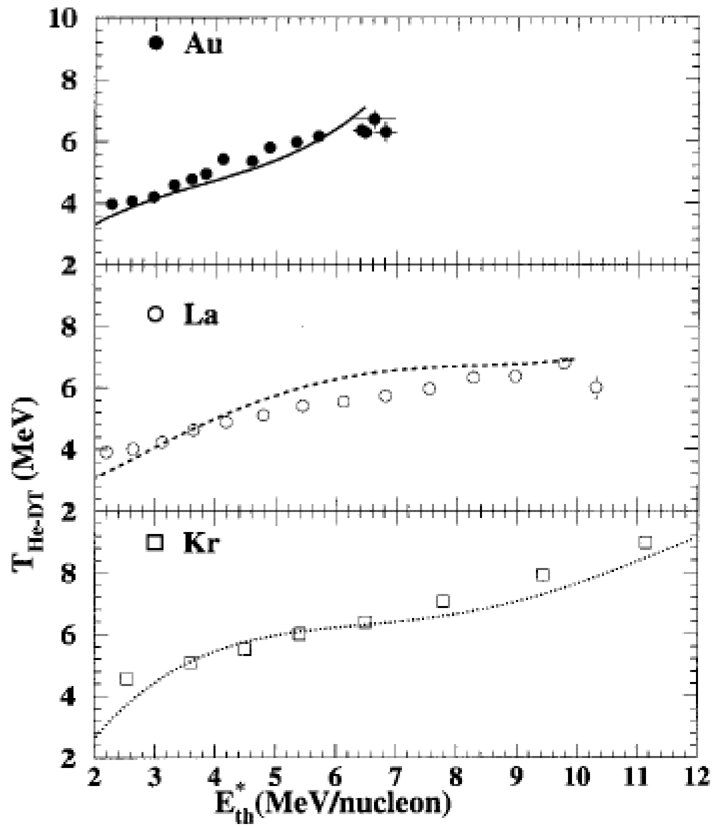


FIG. 19. Caloric curves (T_f vs E^*_{th}/A) for Kr, La, and Au. Points are experimental and curves are from SMM.

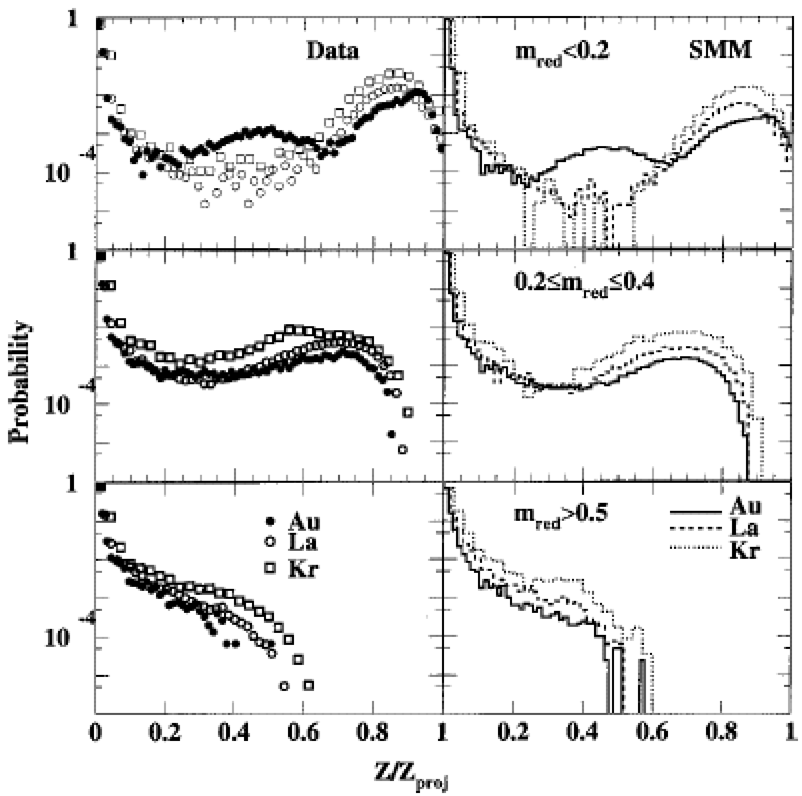
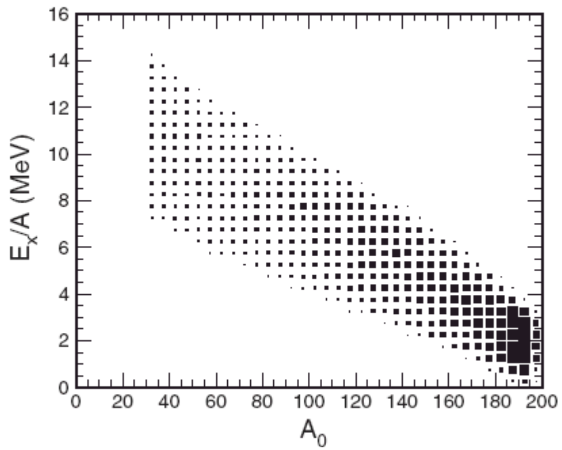


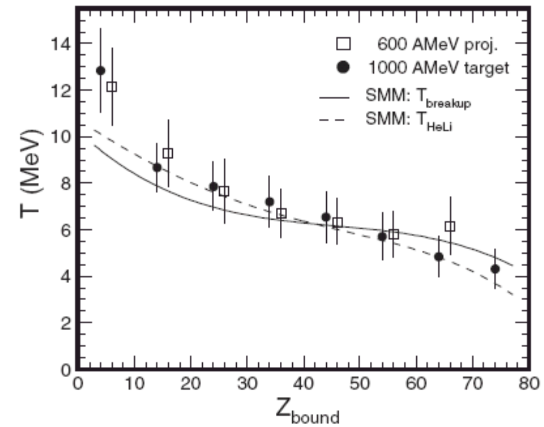
FIG. 24. Second stage fragment charge distribution as a function of $Z/Z_{projectile}$. Results are shown for three reduced multiplicity intervals for both data and SMM.

ALADIN data

GSI

multifragmentation of relativistic projectiles

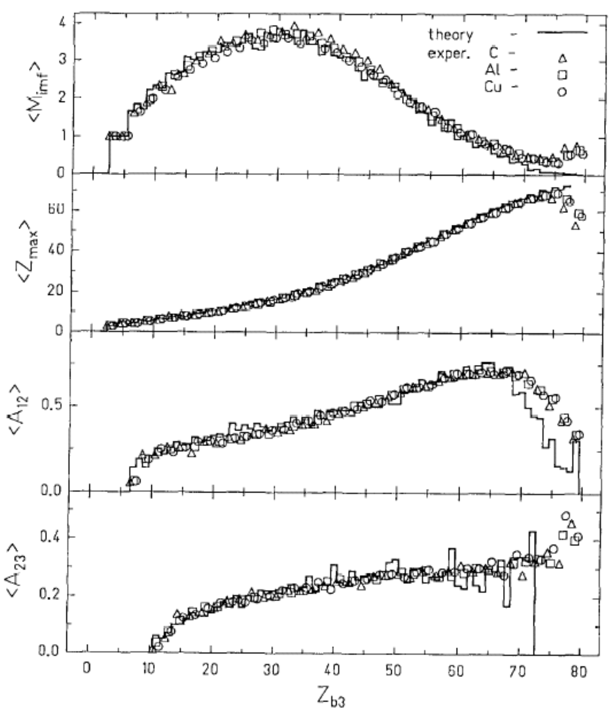




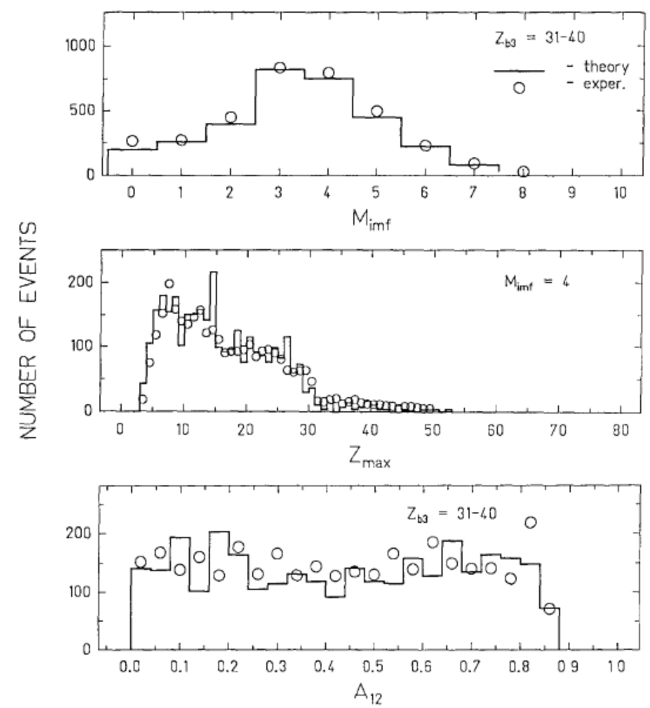
A.S.Botvina et al., Nucl.Phys. A584(1995)737

H.Xi et al., Z.Phys. A359(1997)397

Au(600MeV/n)+C,Al,Cu



Au(600MeV/n)+Cu



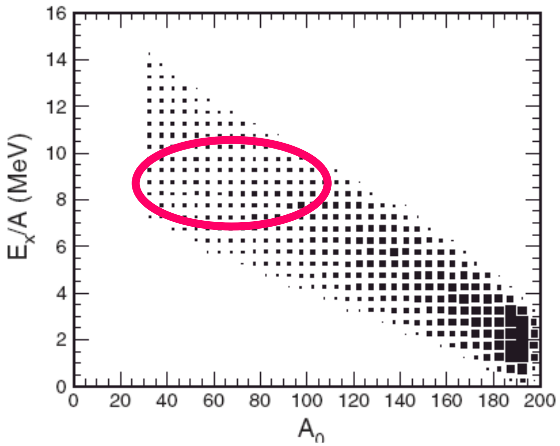
comparison with SMM (statistical multifragmentation model)

Statistical equilibrium has been reached in these reactions

ALADIN data

GSI

multifragmentation of relativistic projectiles



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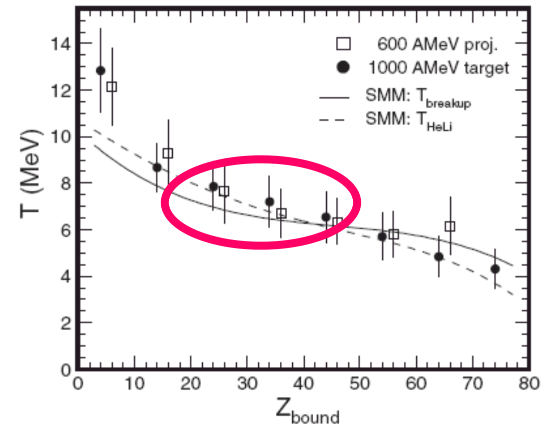

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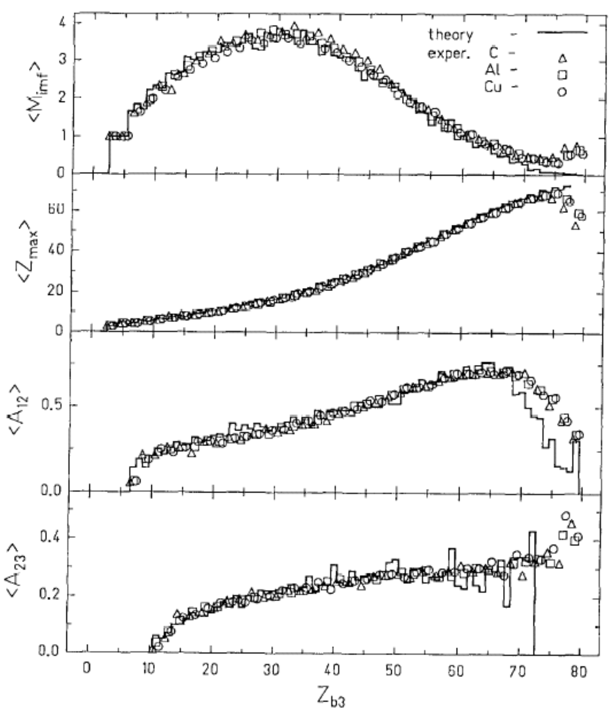

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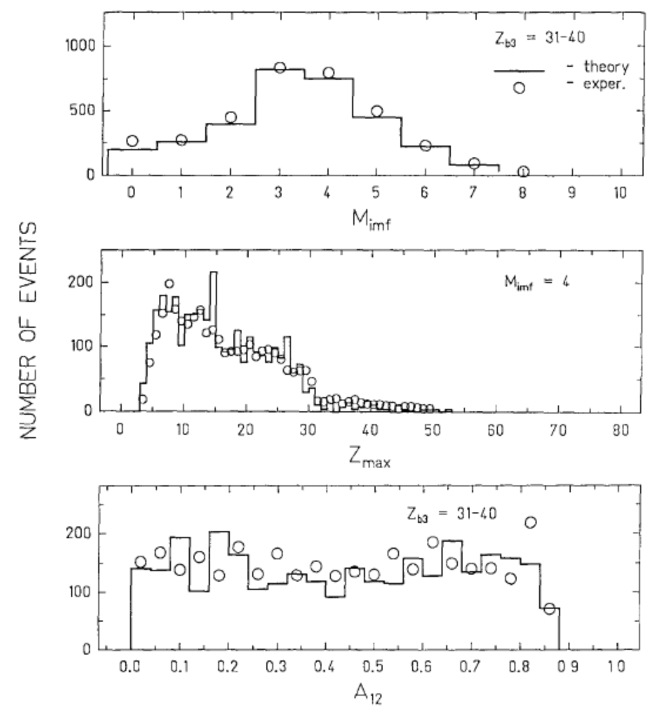
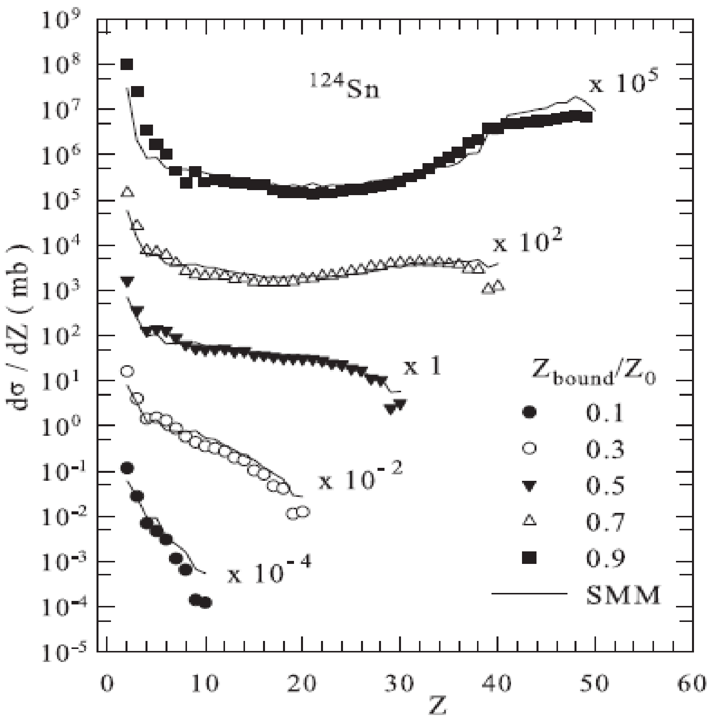


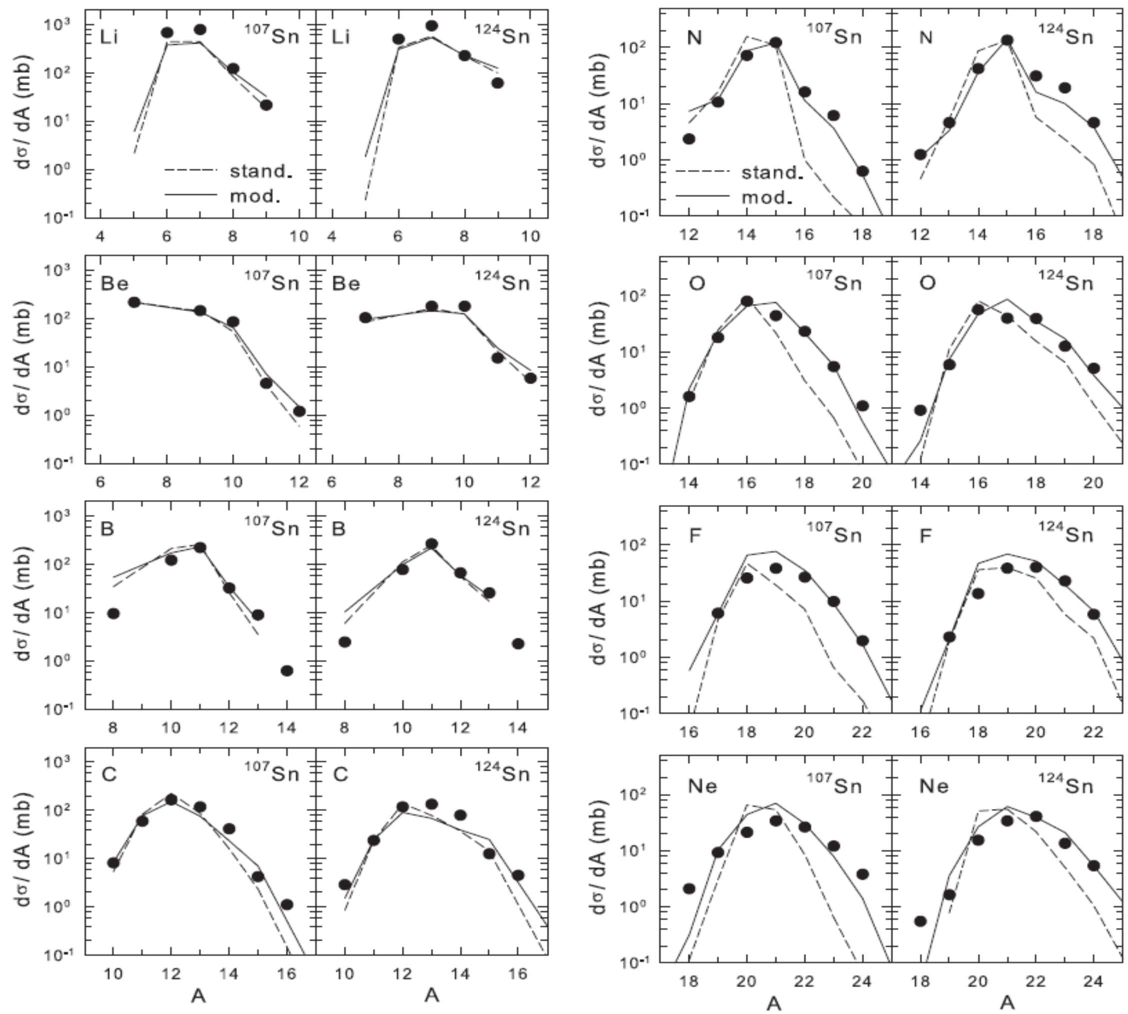
R.Ogul et al. PRC **83,** 024608 (2011) **ALADIN@GSI**

Isospin-dependent multifragmentation of relativistic projectiles

124,107-**Sn**, 124-**La** (600 A MeV) + **Sn** → projectile (multi-)fragmentation

Very good description is obtained within Statistical Multifragmentation Model, including fragment charge yields, isotope yileds, various fragment correlations.

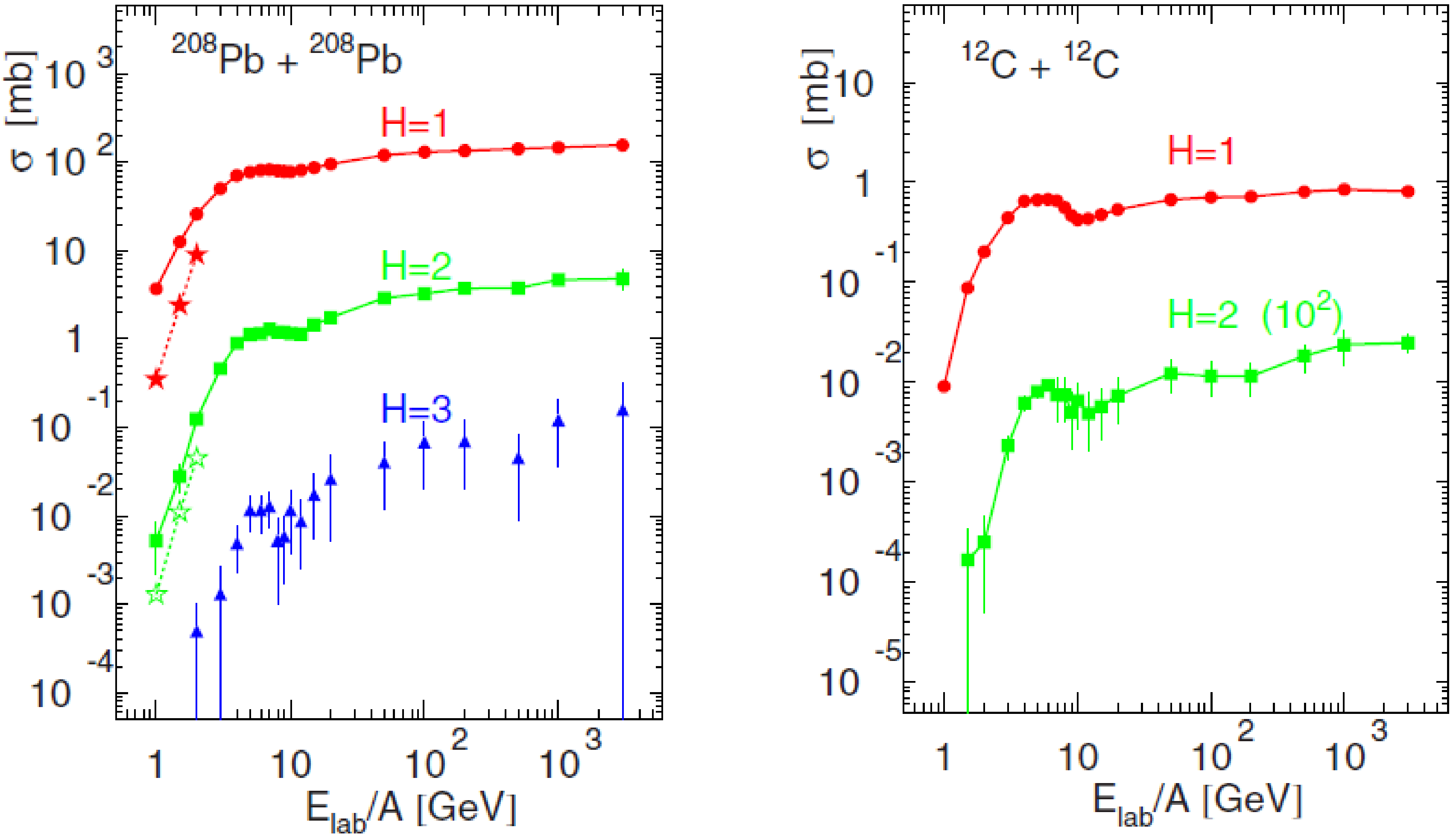




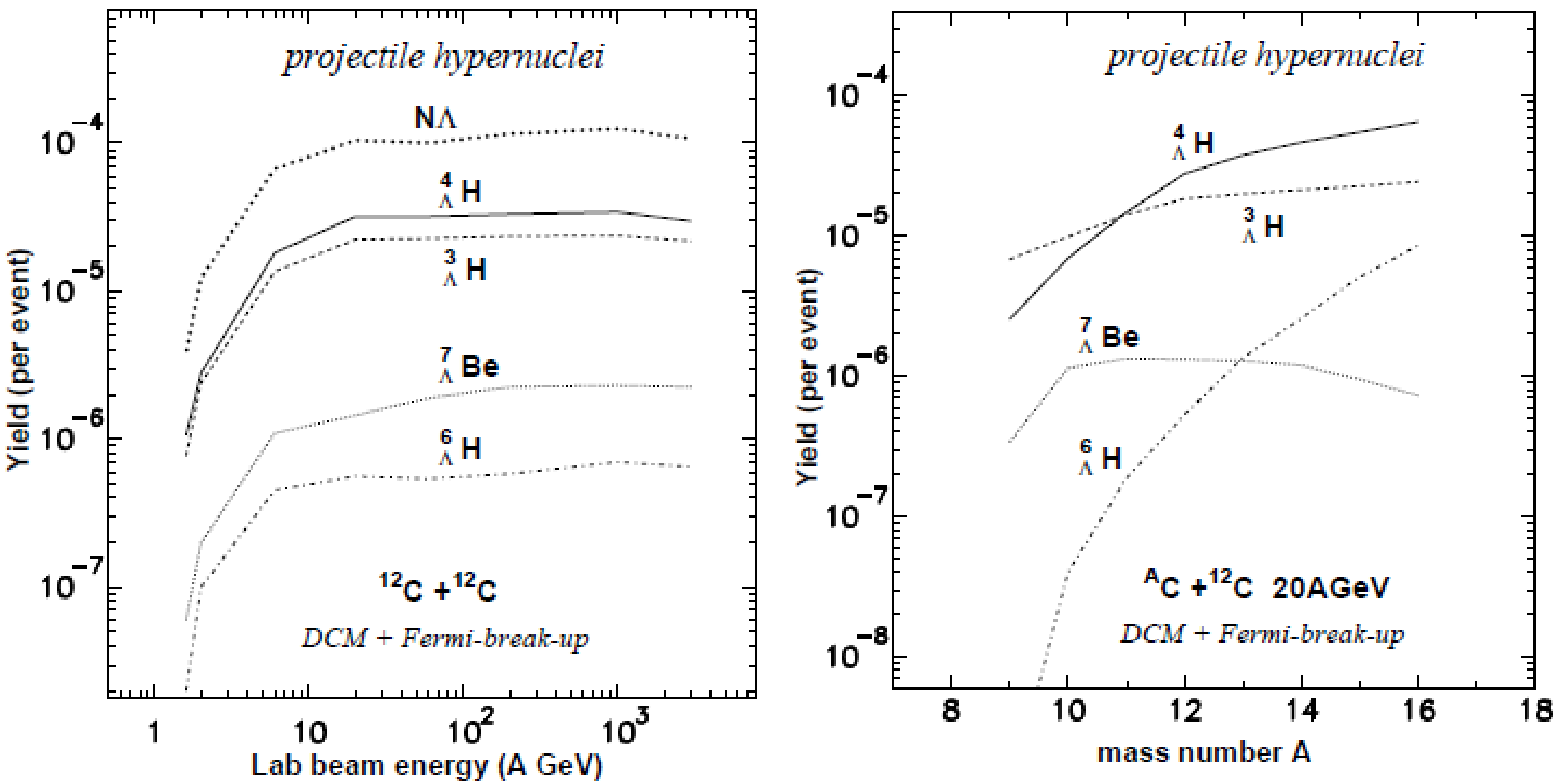
Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

Production of excited hyper-residues in peripheral collisions, decaying into hypernuclei (target/projectile rapidity region).

DCM and UrQMD + CB predictions: Phys. Rev. C95, 014902 (2017)



Production of light hypernuclei in relativistic ion collisions



One can use exotic neutron-rich and neutron-poor projectiles, which are not possible to use as targets in traditional hyper-nuclear experiments, because of their short lifetime. Comparing yields of hypernuclei from various sources we can get info about their binding energies and properties of hyper-matter.

A.S.Botvina, K.K.Gudima, J.Pochodzalla, PRC 88, 054605, 2013

Statistical reaction models can be used not only for the production prediction:

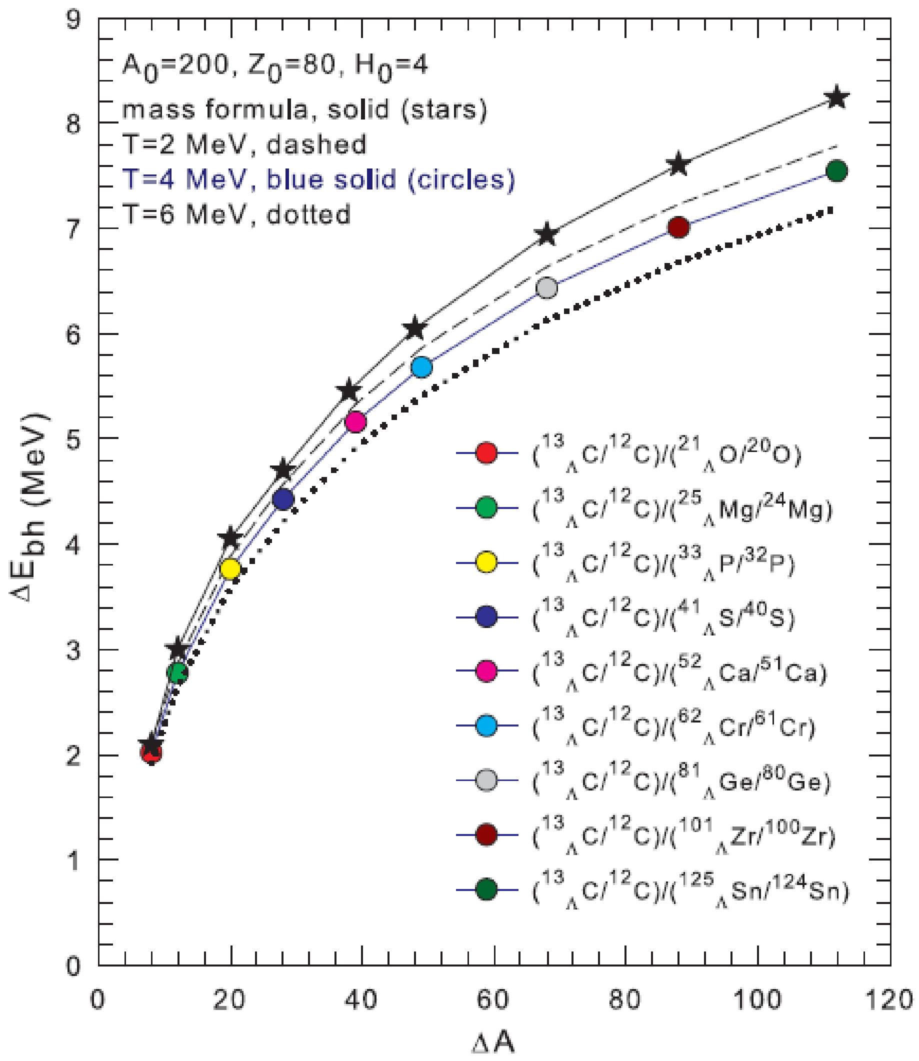
Experimental yields of isotopes can be used for extracting properties of exotic cluster, e.g., the hyperon binding energies

Double ratio method :

ΔE_{bh} **vs** ΔA

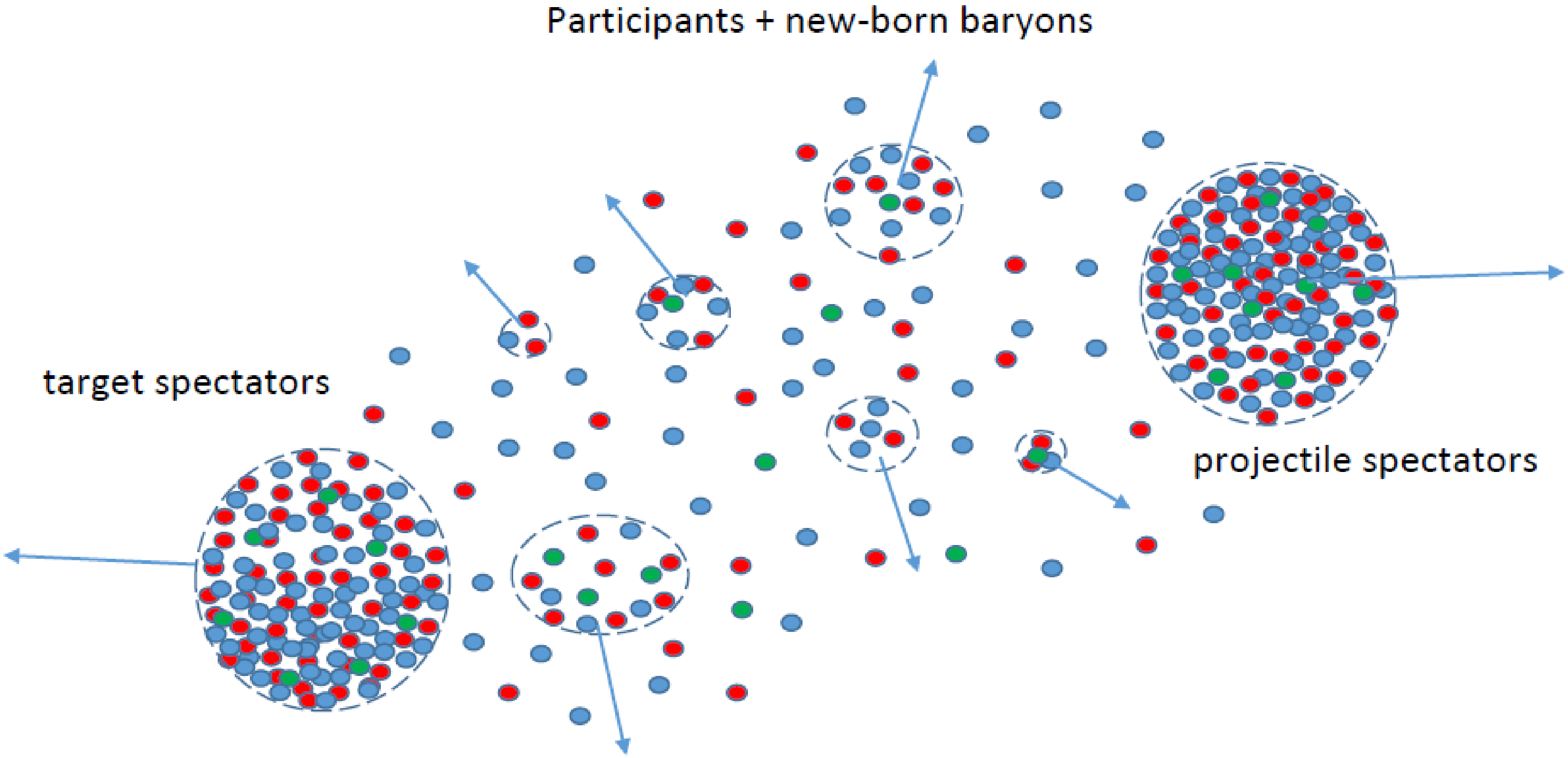
difference of hyperon energies in hyper-nuclei:

Phys.Rev.C98(2018)064603



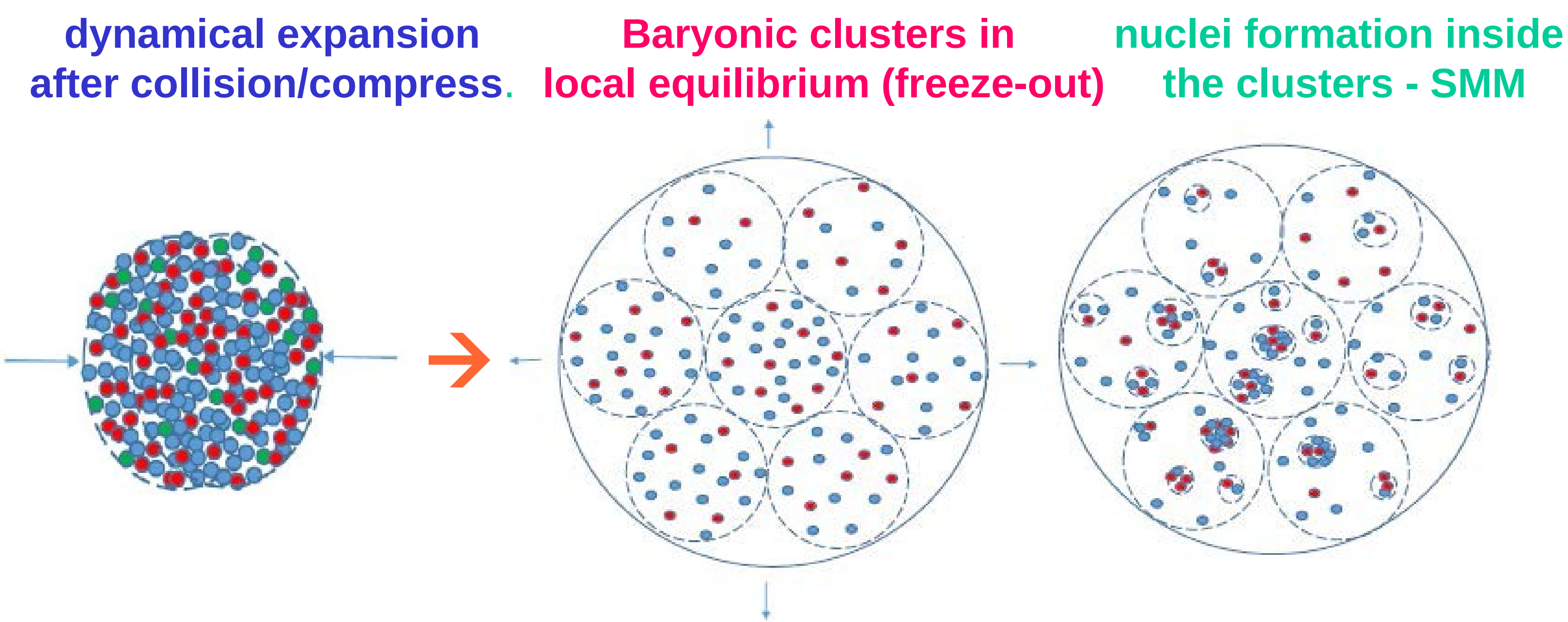
$$\Delta E_{bh} = T \cdot \left[ln\left(\frac{(g_{A_1,Z_1,H}/g_{A_1-1,Z_1,H-1}) \cdot (A_1^{3/2}/(A_1-1)^{3/2})}{(g_{A_2,Z_2,H}/g_{A_2-1,Z_2,H-1}) \cdot (A_2^{3/2}/(A_2-1)^{3/2})}\right) - ln\left(\frac{Y_{A_1,Z_1,H}/Y_{A_1-1,Z_1,H-1}}{Y_{A_2,Z_2,H}/Y_{A_2-1,Z_2,H-1}}\right)\right]$$

Formation of baryon clusters from the dynamically produced baryons as a results of secondary interaction between them, when they are in the vicinity of each other. Note: baryons in clusters can come to equilibrium and the clusters are excited respective to its ground state. This case is realized in Heavy- Ion collisions of medium/high energies.



CENTRAL COLLISIONS

Nuclear system expands to low densities and passes the density around 0.1 of normal nuclear density, which corresponds to the freeze-out adopted in the statistical models. Baryons can still interact and form nuclei at this density. We divide the nuclear matter into clusters in local chemical equilibrium and apply SMM to describe the nucleation process in these clusters.



To check this novel mechanism with controlled models:

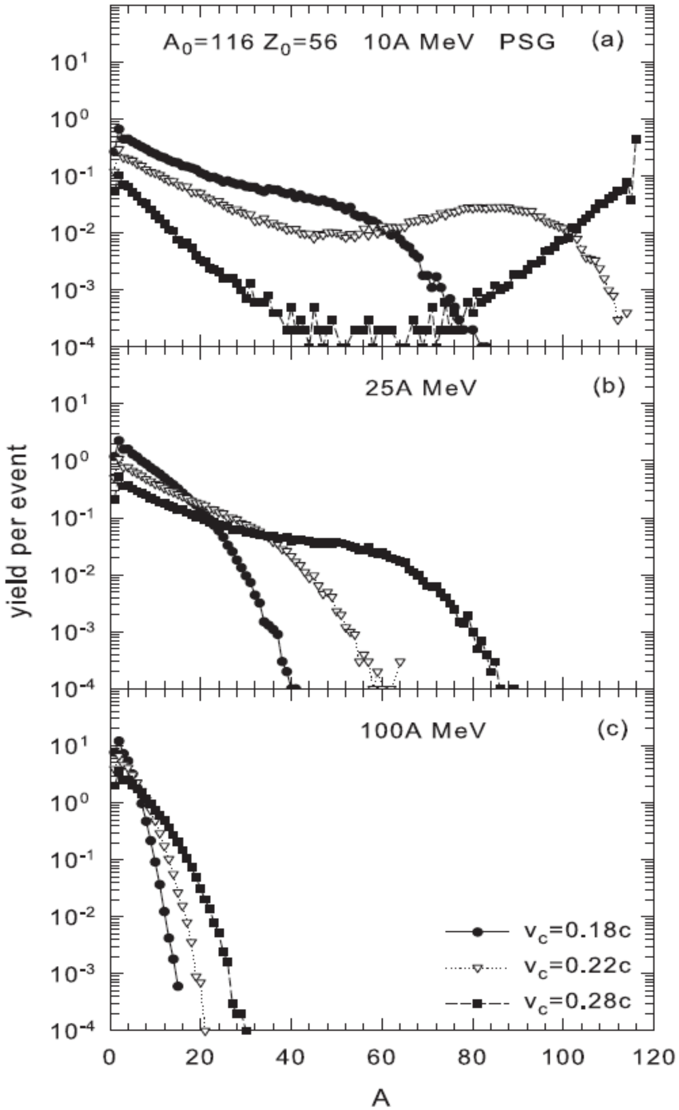
Phys.Rev.C103 (2021) 064602 and arXiv:2203.17092

The dynamical stage is simulated with the phase space generation (PSG) and hydrodynamical-like generation (HYG) methods. They provide very different momenta distributions of baryons which cover the most important limits expected after this stage.

Selection of primary clusters (at low freeze-out density) by using the coalescence of baryon (CB) model (Phys. Lett. B742, 7 (2015)): according to their velocities $|V_i - V_0| \leq V_c$ and coordinates $|X_i - X_0| \leq X_c$.

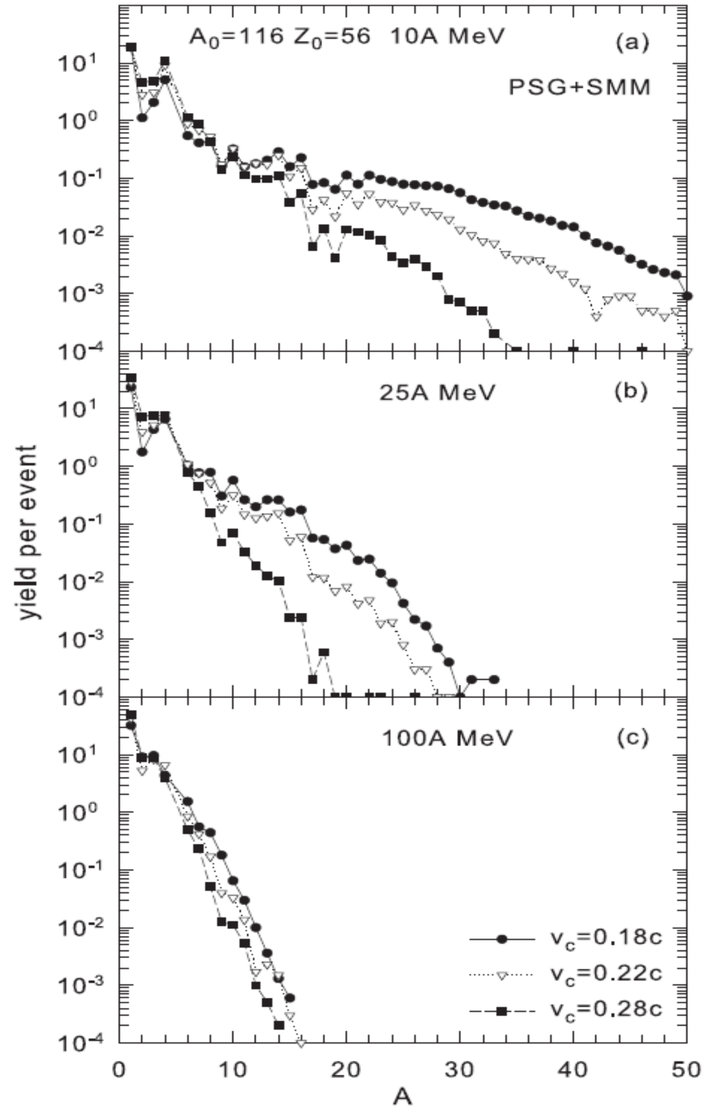
Statistical formation of nuclei inside these clusters with SMM: de-excitation of the excited clusters. The excitation energy (or local temperature) of such clusters is important characteritics for the nuclear matter.

Nuclear system consists of primary clusters in local equilibrium:



→

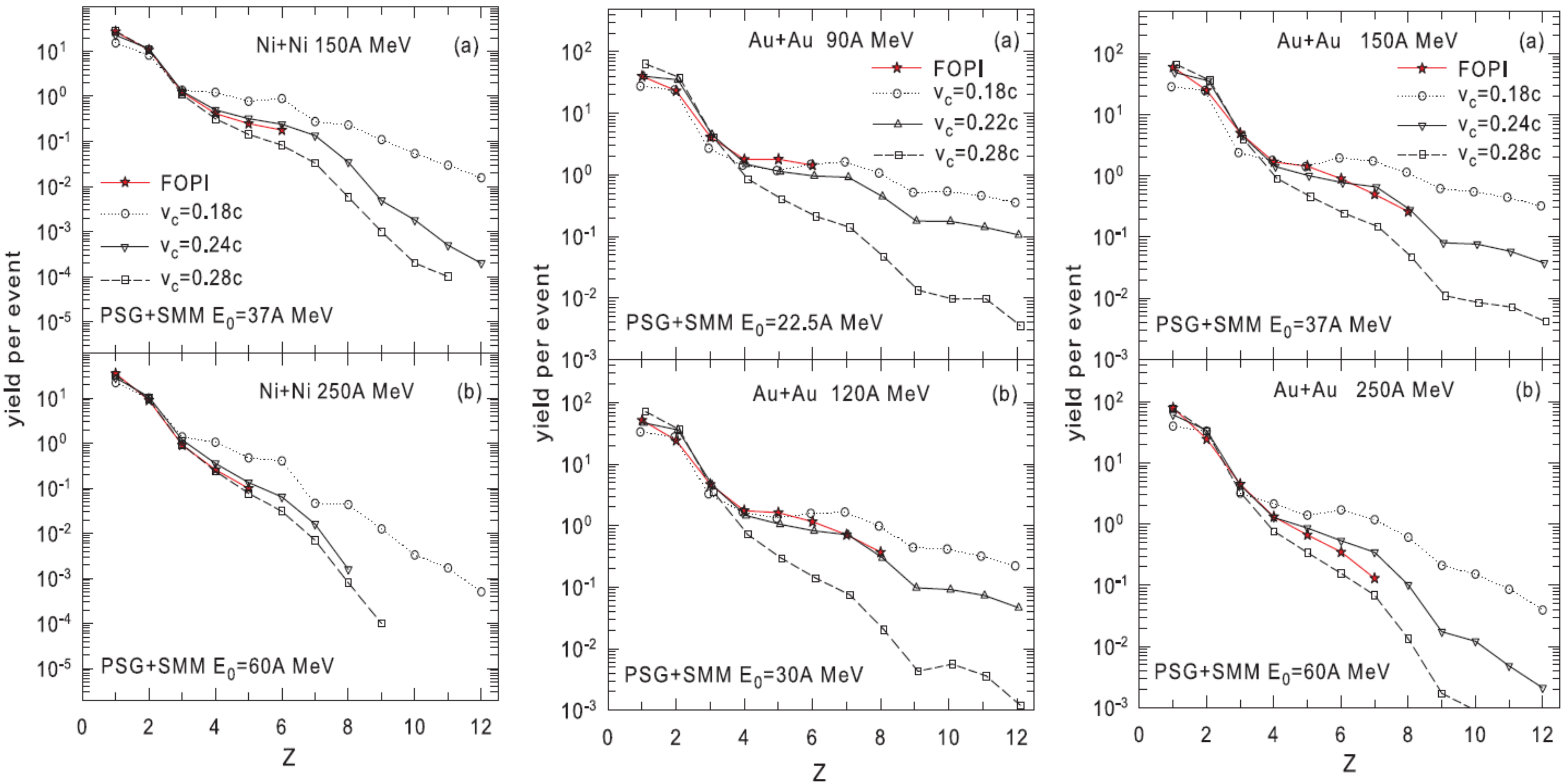
final nuclei after the statistical nucleation (disintegration of the excited clusters via SMM):



For the first, the consistent comparison with FOPI@GSI experimental data - Nucl. Phys. A848(2010)366 - on fragment production in central HI collisions is performed: Both charge yields and flow energies.

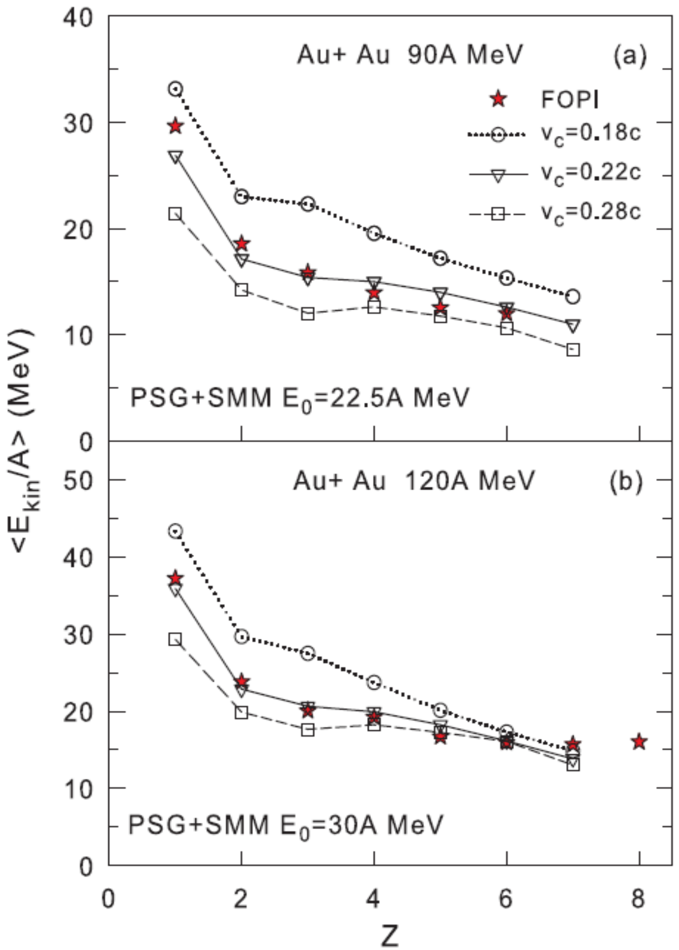
see Phys.Rev.C103 (2021) 064602 and arXiv:2203.17092

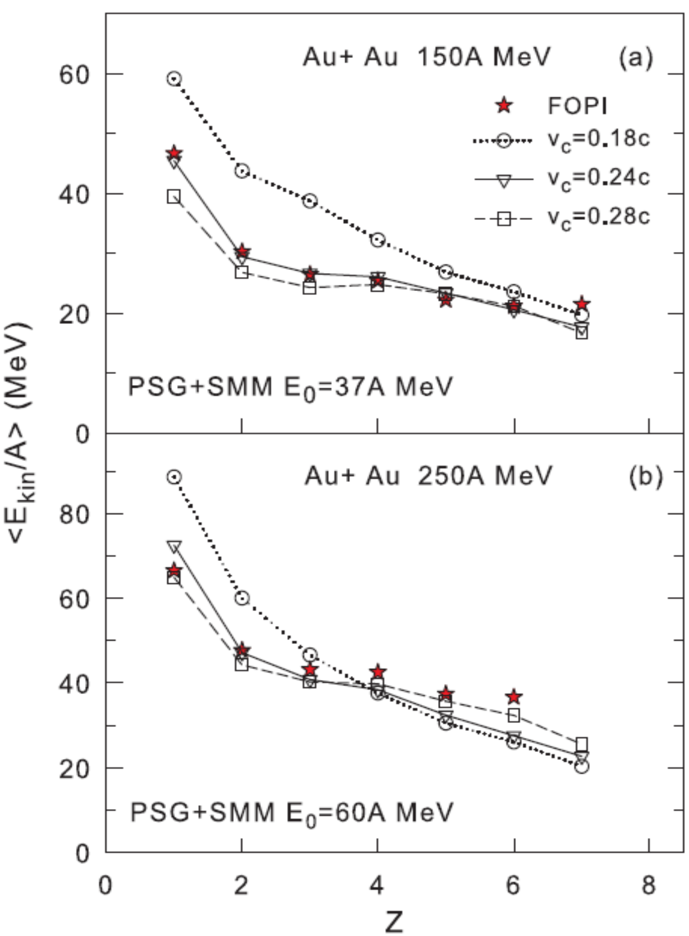
yields of nuclei in different reactions:



(until now the production of nuclei (Z>2) in central collisions was not possible to describe consistently)

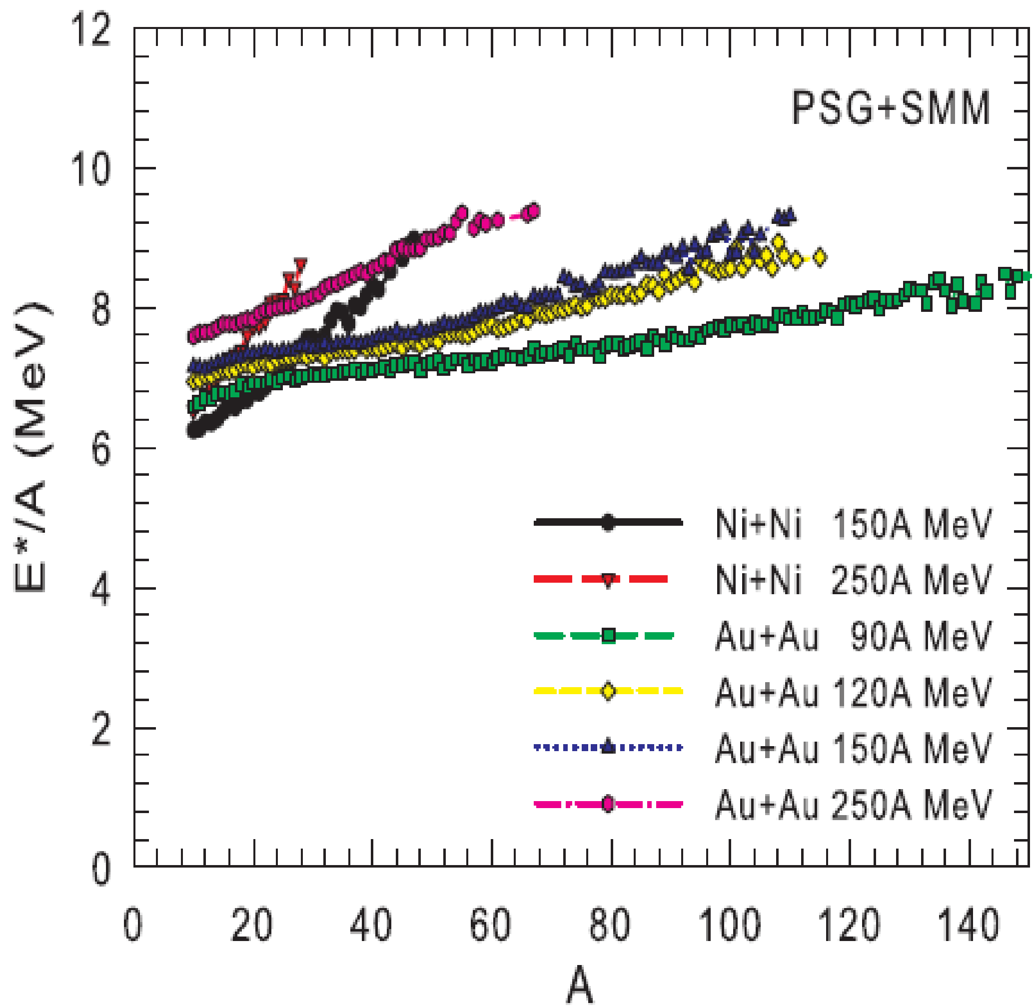
kinetic energies of nuclei in different reactions:





However, the description is possible if there is a limit for the excitation energy of the clusters: 6–10 MeV/nucleon, close to their binding energies. Temperature T=6--8 MeV (according to the statistical model) which corresponds to the coexistence region of the liquid-gas type phase transition in nuclear matter.

We may speak about an universal mechanism for nuclei formation both in peripheral and central heavy-ion collisions , independently on the way how the low density matter is produced: by thermal-like expansion of the excited residues (peripheral col.) or by dynamical-like expansion (central col.)

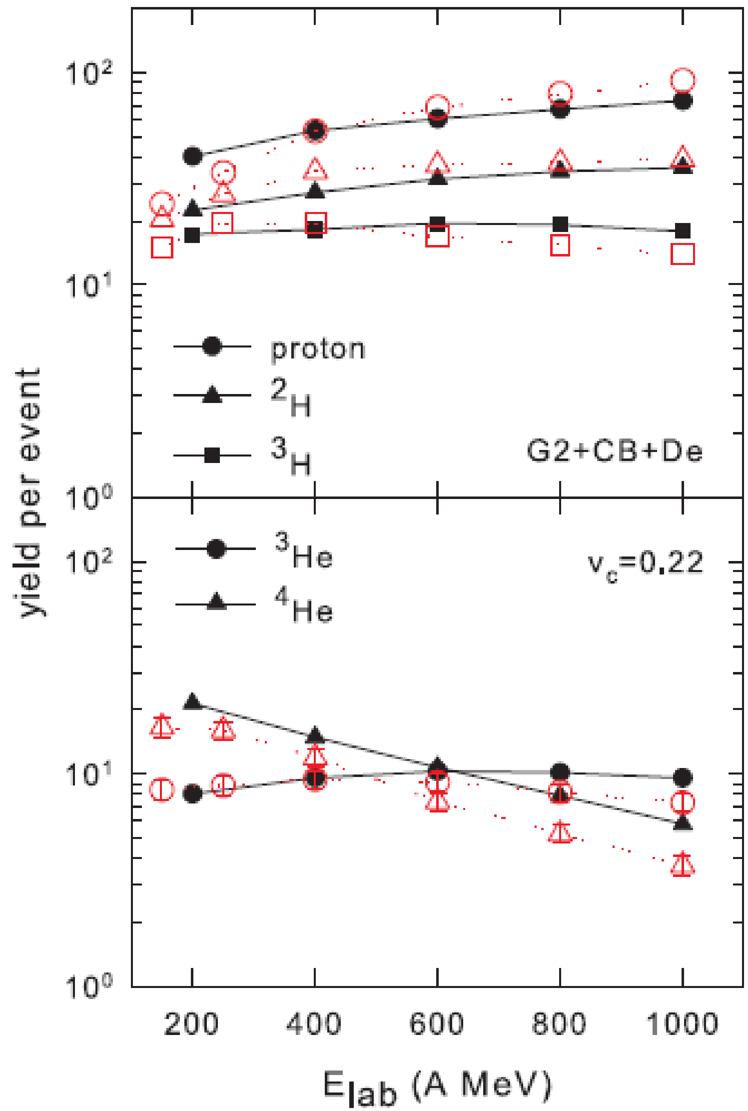


Important beam energy dependence of the light nuclei yields in Au+Au relativistic central collisions can be explained within our approach too.

Note: in simplistic coalescence picture yields of 3He are larger than 4He yields at all energies.
FOPI experimental data (red symbols) show intersection with increasing energy.

Relative behavior of yields of 3He and 4He with energy is important confirmation of the nucleation via the statistical mechanism

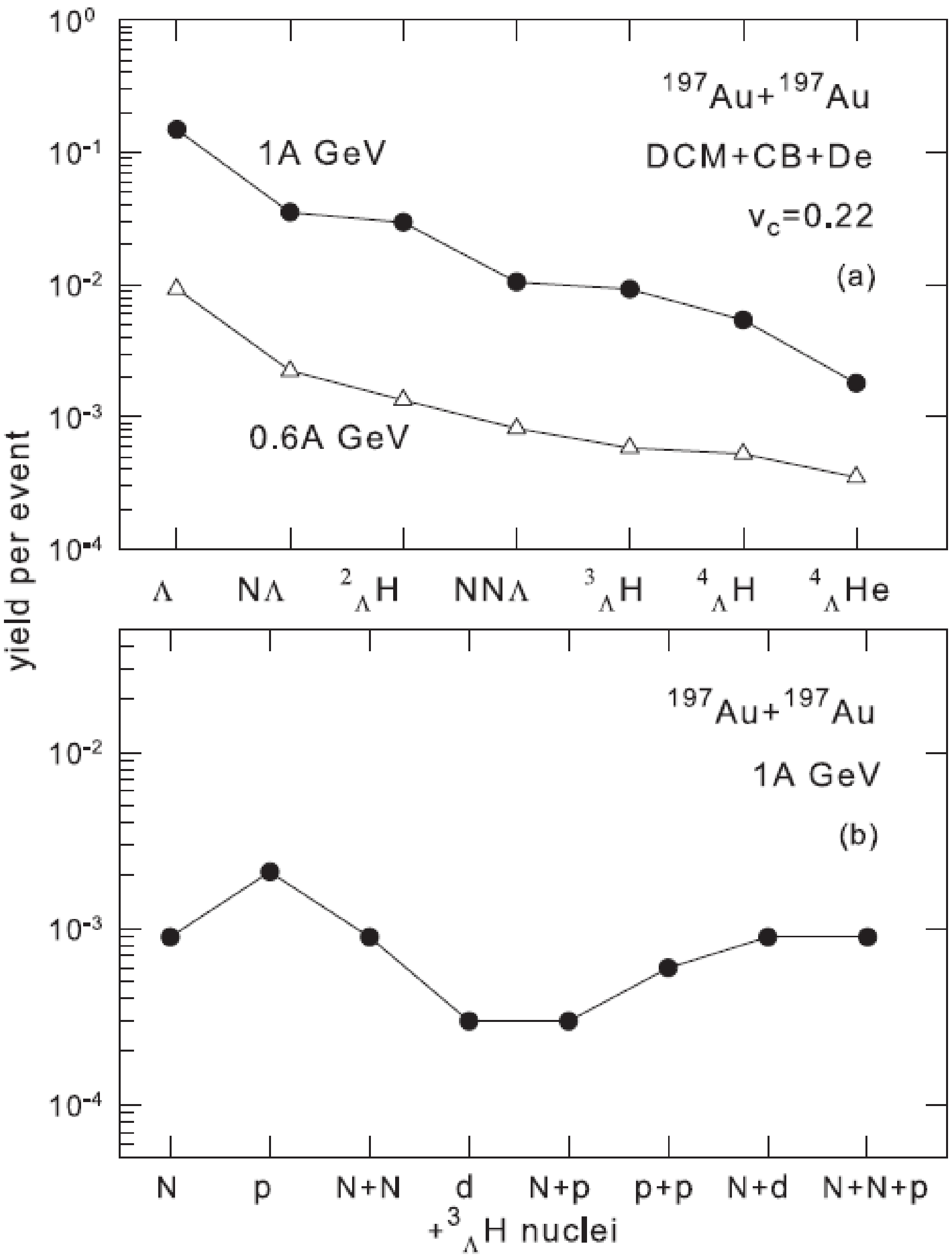
Phys.Rev.C103 (2021) 064602



Production of hypernuclei in HI central collisions

Basing on this general mechanism we can predict the hypernuclei yields in relativistic central collisions too. Many different light hypernuclei can be produced. The correlations between nuclear species exist and it can be used for their identification.

Phys.Rev.C103 (2021) 064602



Conclusions

Collisions of relativistic ions are promising reactions to search for nuclear clusters, exotic clusters with very different isospin, including hypernuclei. These processes can be simulated within dynamical and statistical models.

Mechanisms of formation of hypernuclei in reactions: Strange baryons (Λ, Σ, Ξ, …) produced in particle collisions can be transported to the spectator residues and captured in nuclear matter. Another mechanism is the nucleation of baryons at subnuclear density. It leads to light clusters and is effective at all rapidities. Novel mechanism: The matter is divided into excited baryon clusters in local equilibrium and after the cluster decay the nuclei and hypernuclei of all sizes (and isospin), including short-lived weakly-bound states, multi-strange nuclei can be produced.

Advantages over other reactions: there is no limit on sizes and isotope content of produced exotic nuclei; probability of their formation may be high; a large strangeness can be deposited in nuclei.

Properties of hypernuclei (hyperon binding) can be addressed in novel way!

Correlations (unbound states) and lifetimes can be naturally studied.

EOS and the symmetry energy of hypermatter at subnuclear density and hyperon interactions in exotic nuclear matter can be investigated.